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Volcanic aerosol perturbations and strong El Niño events: No general correlation

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Abstract. We test the hypothesis that El Niño/Southern Oscillation (ENSO) events are caused or enhanced by volcanic aerosol perturbations using two methods: 1) A case-by-case comparison of the 16 strongest El Niño events of the last 150 years with the characteristics of the largest concurrent volcanic events, and 2) Comparison of the timing of strong El Niño events and the independently determined record of stratospheric optical depth (τ) perturbations. Many eruptions that occurred near times of strong El Niño years produced small amounts of stratospheric aerosols, in many cases the relative timing of the two events argues against triggering. The correlation of 4 of 11 peaks in global stratospheric optical depth ($\tau \geq 0.025$) within 3 years of strong El Niño events over the last 150 years is what would be expected by chance. Moreover, five strong El Niños occurred between 1915 and 1960, when the stratosphere was largely free of volcanic aerosols. Of the three strongest tropical volcanic aerosol perturbations that coincided with or were followed by strong El Niños in the period studied (Krakatau in 1883, El Chichón in 1982, and Pinatubo in 1991), the two modern ones occurred after the earliest SST warming of the El Niño events. The coincidence of these two phenomena indicates no causative relationship.

Introduction

Several studies over the past decade have suggested a causative link between volcanic eruptions and El Niño-Southern Oscillation (ENSO) events [*Handler*, 1984, 1986, 1989; *Handler and Andsager*, 1990, 1993; *Hirono*, 1988]. The problem has been how to test for a cause-and-effect relationship. *Handler* (1989), proposed that even very small radiative perturbations (~1%) in the tropics could lead to triggering of El Niños, and therefore, volcanic eruptions that produced aerosol clouds only slightly above background could generate or amplify El Niños. *Handler's* proposed mechanism, which is based on very small radiative effects and is sensitive to the timing and latitude of the eruptions, is difficult to test in theory and practice. *Hirono* [1988] proposed a more specific model in which the 1982-83 El Niño was triggered by ash and aerosols from the El Chichón eruption. Studies using a Global Climate Model suggest that *Hirono's* mechanism cannot explain the relationship between the timing and location of the 1982 El Chichón eruption and the following ENSO event [*Graf et al.*, 1992; *Robock et al.*, 1995], and other climate model simulations investigating possible connections between ENSO and low-latitude volcanism have concluded that increases in stratospheric aerosols cannot in general trigger ENSO events [*Robock and Liu*, 1994]. Moreover, *Nicholls* [1988] showed that for a set of ten eruptions occurring near ENSO events, sea-surface pressure changes considered indicative of the onset of ENSO preceded the eruptions, and *Robock and Free* [1995] found no correlation between the SOI (Southern Oscillation Index) and standard volcanic indices (e.g., the Volcanic Explosivity Index or VEI).

It is also recognized that warming due to ENSO has masked potential cooling after several major eruptions, confusing the issue of climate anomalies and forcing at these times [e.g., *Angell*, 1990]. These climate anomalies can be explained by enhancement of a natural coupled mode of tropospheric-stratospheric circulation, which can apparently occur with or without volcanic aerosol perturbations [*Graf et al.*, 1993]. *Rasmussen and Carpenter* [1982] showed that ENSO events are usually well underway by March of an El Niño year. Thus, for an eruption to be directly involved in the onset of an El Niño, it should occur at the end of the previous year, or early in the year of the El Niño event.

Considering these problems, we decided to test the more limited proposal that if El Niños and eruptions are related, then the strongest El Niños should be related to the strongest volcanic perturbations. While it is well established that volcanic eruptions can have a measurable impact on global and hemispheric climate and atmospheric circulation [e.g. *Rampino and Self*, 1982; *Self and Rampino*, 1988; *Sigurdsson*, 1990; *McCormick et al.*, 1995], previous studies evaluating eruptions and ENSO have typically utilized eruptions with a volcanic explosivity index (VEI) ≥ 4 [*Newhall and Self*, 1982], regardless of considerations as to whether these eruptions were capable of producing significant aerosol clouds. We here assess the timing, magnitude, location, and aerosol-producing capability of explosive eruptions that have occurred at times of strong El Niños in order to investigate whether a causative link between these two phenomena may exist.

Timing of Volcanic Eruptions and Strong ENSO Events

We adopted the previous compilation of ENSO events by *Quinn et al.* [1978] and later sources [*Quinn and Neal*, 1992; *NOAA*, 1994] to identify the strongest El Niños of the past 150 years (Table 1). We use only the strongest El Niño events (S, S+, VS) to avoid signal to noise problems in defining El Niño years. We then examined evidence pertaining to all volcanic eruptions occurring in the year and preceding year of these fifteen strongest ENSOs, as given in the available volcanological compilations [*Simkin et al.*, 1981; *Simkin and Siebert*, 1994; *McClelland et al.*, 1989; *Newhall and Self*, 1982; *Zielinski et al.*, 1994; *Robock and Free*, 1995; *Newhall and Dzurisin*, 1988]. We selected the eruptions in those years that were a) the largest in terms of magma output, b) highly explosive, and c) were most likely, on grounds of magma type or known record of activity, to have produced extensive tropospheric or stratospheric ash or sulfate aerosols. These are shown listed with the years of the strongest El Niños in

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Table 1. Years of the Strongest El Niños and the Closest Coincident Volcanic Eruption, 1840-Present

ENSO Year	Volcanic Eruption	Lat.	Date*
1844-45	Hekla, Iceland	65N	9/2/1845
1871	none		
1877	Cotopaxi, Ecuador	0.5S	6/25/1877
1884	Krakatau, Indonesia	6S	8/26-27/1883
1891	none		
1899	Dona Juana, Colombia	1.5N	11/13/1889
1911	Taal, Philippines	14N	1/30/1911
1917-18	Tungurahua, Ecuador	1.5S	4/5/1918
1925	Raikoke, Kurile Isl.	48N	2/15/1924
1932	Cerro Azul, Chile	35.3S	4/10/1932
	Fuego, Guatemala	14.5N	1/21/1932
1941	none		
1957	Bezymianny, Kamchatka	56N	8/22/1956
1972	Fuego, Guatemala	14.5N	9/14/1971
1982-83	El Chichón, Mexico	17N	3/28; 4/4/1982
1991-92	Mt. Pinatubo, Philippines	15N	6/15/1991

*Dates are given as month/day/year.

Table 1, and are similar to those volcanic events selected by previous workers [e.g., *Handler and Andsager*, 1993].

In the list of strong ENSO events (Table 1), those in 1844-45, 1871, 1891, 1917-18, and 1941 are notable in that no known significant eruption occurred at the critical time for triggering the event. The 1871 El Niño occurred 2 years after the explosive eruption of Purace (Colombia) in 1869. The 1844 ENSO was well under way by the time of the high-latitude September, 1845 eruption of Hekla, Iceland, and similarly for the ENSO of 1917-18 and the March, 1918 eruption of Tungurahua, Ecuador. The 1941 period shows a variable ice-core acidity anomaly in Greenland [*Lyons et al.*, 1990], but the source is not known, and no major eruptions were recorded for that year. The ice-core peak is most likely the result of local Icelandic eruptions [*Zielinski*, 1995].

We now examine the remaining coincident events, except for 1884, 1982 and 1991, which will be discussed later.

1877 (Cotopaxi, Ecuador): The 25-26 June, 1877 climax of the Cotopaxi eruption did not produce a stratospheric eruption column, and yielded a relatively small volume of pyroclastic material (< 2×10^8 m^3). Thus, it was probably both too late and too small to have had much effect on the El Niño in the same year.

1899 (Dona Juana, Colombia): Dona Juana had a growing lava dome that was consistently active from 1897 to 1906, but with peak activity in mid- to late 1899. This type of activity at the low levels suggested by contemporary reports does not produce significant volcanic aerosol clouds.

1911 (Taal, Philippines): Although locally devastating, the January 30, 1911 explosions from Taal were comparatively small, and probably did not reach the stratosphere. The volcano has the potential to release significant amounts of volcanic gases, but the 1911 eruption involved only a small volume of magma (<<1 km^3). Whether Taal produced significant aerosols is difficult to determine from the Greenland ice-core record because the northern hemisphere signal is mixed with that of the great Katmai-Novarupta event of 1912 [*Zielinski*, 1995].

1925 (Raikoke, Kurile Isl.): Raikoke volcano produced the only significant recorded eruption between 1920 and 1928 on 15 Feb. 1924, and thus could have been the source of a Greenland ice-core signal recorded in the 1925 period at several sites, although no significant aerosol peaks were observed at this time [*Sato et al.*, 1994]. *Zielinski* [1995] attributes the ice-core peak to tropospheric transport from this high-latitude eruption.

1932 (Fuego, Guatemala; Cerro Azul, Chile): The small January 21-22 eruption of Fuego may have produced a stratospheric eruption column >17 km high. It was followed in April by one of the largest eruptions in this century, that of Cerro Azul (35° S), but neither eruption yielded a large stratospheric optical depth (Figure 1) and the total production of H_2SO_4 aerosols was probably < 2 Mt.

1957 (Bezymianny, Kamchatka): The short-lived explosion of Bezymianny volcano on March 30, 1956 produced a very high eruption column, but released a comparatively low amount of magma and, like Mount St Helens in 1980, probably yielded only a small amount of sulfur gases to the atmosphere. The explosion occurred a year prior to the 1957 ENSO event, and considering its high latitude location (56° N), was unlikely to have produced radiative effects in the tropics. Signals in Greenland ice and snow pits are most likely from tropospheric transport of aerosols [*Zielinski*, 1995].

1972 (Fuego, Guatemala): The small eruption of September, 1971, with columns < 15 km in height, produced only about 10^4 tons of SO_2 [*Stoiber and Rose*, 1973], and was thus incapable of producing more than a local short-lived tropospheric aerosol cloud. The larger 1974 eruption of Fuego, which produced stratospheric aerosols (Fig. 1), is not associated with an El Niño year.

Aerosol Optical Depth and Strong El Niños

Figure 1 shows a record of stratospheric optical depth perturbations compiled from direct observations of atmospheric opacity [*Sato et al.*, 1993; *Stothers*, 1996] and El Niño years. Even if we use the relatively conservative cutoff of $\tau = 0.025$, it is clear that many strong El Niños have occurred at times when volcanic stratospheric aerosols were at or close to background levels. El Niños occurred with or without significant volcanic perturbations, and there is no general relationship between the onset of an ENSO event and periods of elevated stratospheric optical depth. Five of the 14 strong El Niños in Table 1 occurred in the 45-year period from 1915 to 1960, which lacks any large aerosol perturbations (Fig. 1).

Using a cutoff of $\tau = 0.025$ may be too conservative, however, as a release of at least 5-7 megatons (Mt) of SO_2 from a tropical eruption is required to significantly change the radiation budget of the tropics such that surface ΔT is greater than the interannual noise level (~0.2-0.3°C), equivalent to a hemispheric optical depth of τ ~0.10 (Fig. 2).

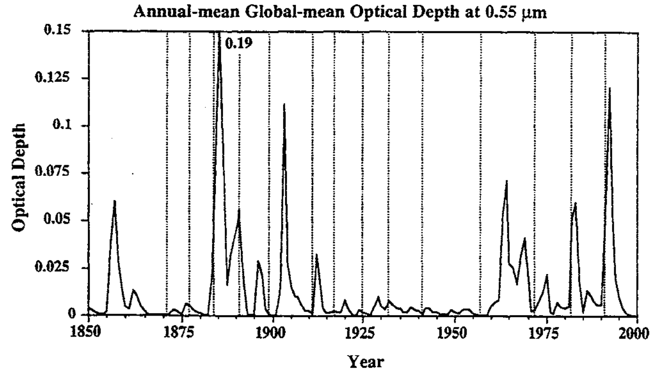

Figure 1. Global mean optical depth for 1850-1991 [after *Sato et al.*, 1993; *Stothers*, 1996] and years of the strongest ENSO events [after *Quinn et al.*, 1978; *Quinn and Neal*, 1992]. ENSO peaks are shown by vertical dashed lines.

If we assume that a correlation exists when a strong El Niño event occurs within three years of the peak optical depth perturbation, then the El Niño 'window' is 3x14 or 42 years, 28% of the full 150 year record. By chance alone, we would expect that 3 or 4 of the 11 optical depth peaks (27-36%) would fall within 3 years of an El Niño, and the actual value is 4 of 11. The three-year time window is most likely too large, as the e-folding time for the conversion of SO_2 to H_2SO_4 aerosol in the stratosphere is about 30 days, and during this period most of the ash and tropospheric aerosols from an eruption will fall out. The e-folding time for the longer lived stratospheric aerosols is about a year [*Stothers*, 1996]. Moreover, tropical stratospheric volcanic clouds can circumnavigate the globe and begin meridional spreading in about three weeks to a month [*Robock and Matson*, 1983; *McCormick et al.*, 1995]. Thus, by our estimates, a candidate eruption should occur at least one month prior to the onset of ENSO conditions, and release at least 5 Mt of SO_2. Note, however, that the 1963 eruption of Mt Agung (Bali) released ~7 Mt of SO_2 [*Self and King*, 1996], and produced a significant tropical aerosol cloud (Fig. 1), but was not associated with a strong El Niño. Higher latitude eruptions, in the event that they could produce conditions necessary to trigger an El Niño, would also have to release at least 5 Mt of SO_2.

Large Aerosol Perturbations and Strong ENSO Events

Of the original list of coincident events examined, three correlative strong ENSO/large eruption pairs warrant further consideration: 1884 (Krakatau, Indonesia, late August, 1883), 1982-83 (Volcan El Chichón, Mexico, late March/early April, 1982), and 1991-92 (Mt Pinatubo, Philippines, mid-June, 1991). These eruptions produced large aerosol clouds: Krakatau > 10-20 Mt [*Zielinski*, 1995], El Chichón 13 Mt [*Kent and McCormick*, 1988], and Pinatubo 28 Mt of aerosols [*McCormick et al*, 1995], and all three events caused significant radiative anomalies in the tropics [*Sato et al.*, 1993; *Stothers*, 1996] (Fig. 1).

However, in detail, the timing of the major explosions of both El Chichón and Pinatubo seems to have occurred after the onset of

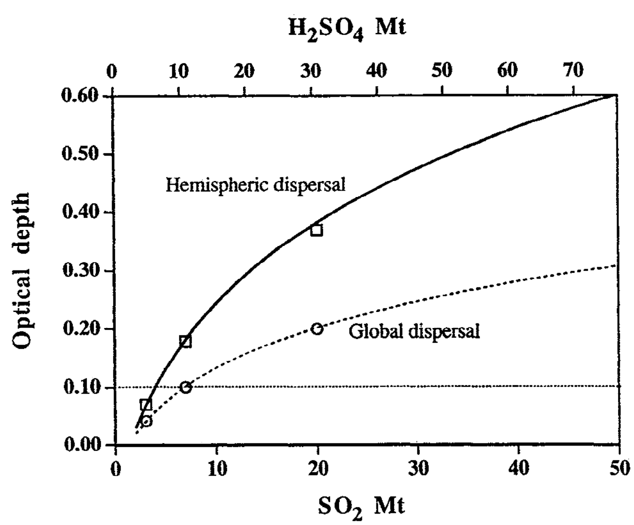

Figure 2. Plot of model optical depths derived from various atmospheric loadings of SO_2 (Mt = megatons = 10^{12} g) for aerosol clouds dispersed globally and in a single hemisphere, based on *Zhao et al.* [1995] and our unpublished model results. Upper scale shows theoretical yield of H_2SO_4 (not sulfate aerosol) from SO_2 loadings.

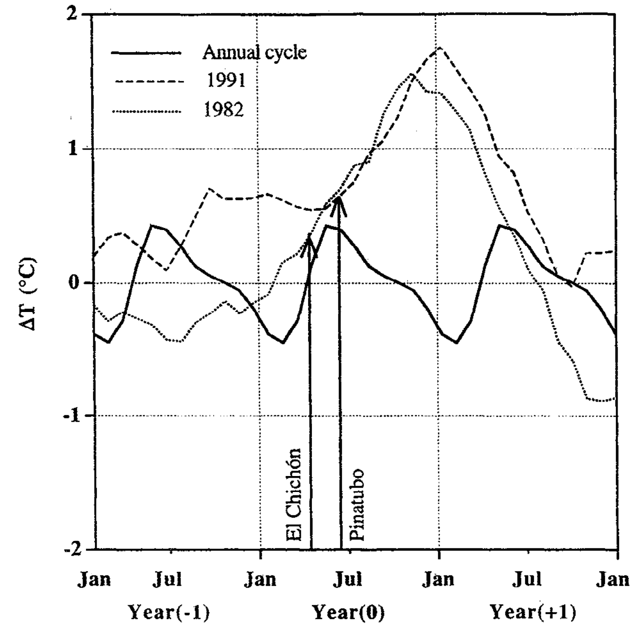

Figure 3. Central Pacific (170W-155W, 55-5N) climatological SST annual cycle and monthly SST anomalies in the years preceding and following the 1982 and 1991 El Niño events [from *Wang*, 1995] with timing of climactic phases of El Chichón and Mount Pinatubo eruptions shown. SST warming in this region indicates earliest onset of these two ENSO events because the associated SST anomalies developed from central Pacific and spread to eastern Pacific.

conditions considered characteristic of ENSOs for those particular years. Figure 3 shows monthly sea-surface temperature (SST) in the central tropical Pacific [*Woodruff et al.*, 1987] for the climatological annual cycle, and SST anomalies for the 1982-83 and 1991-92 El Niño years, with the timing of the El Chichón and Pinatubo eruptions superimposed. Positive SST anomalies in this region occurred prior to both eruptions, although the 1991-1992 warming event greatly increased after Pinatubo erupted. Also it should be noted on Figure 3 that the 1991-1992 SST anomaly appears to be greater (more warming) than that of 1982 but this is not the case because the pre-1991 SST in the central Pacific was warmer. The 1982 ENSO was the stronger, as indicated by the largest SST anomaly in the eastern Pacific this century [*Rasmussen and Wallace*, 1983].

The remaining Krakatau 1883 case cannot be evaluated in detail because the timing of the strong 1884 ENSO event is not well documented [*Quinn and Neal*, 1992]. Historic studies of optical depth show that in early 1884 a considerable aerosol load (τ = 0.125; Figure 1) remained in the tropical and extra-tropical stratosphere from the Krakatau eruption [*Stothers*, 1996].

The association of the three strongest aerosol optical depth perturbations of the tropics in this period (Krakatau 1883, El Chichón 1982, and Pinatubo 1991) with strong El Niños may leave open the question of whether some El Niños can be enhanced by concurrent large radiative perturbations. However, we note that the very strong 1982 El Niño occurred while the El Chichón aerosol cloud of ~13Mt maximum mass [*Kent and McCormick*, 1988] was dispersing in the stratosphere, whereas the rather weaker 1991-1992 El Niño occurred during the dispersal of the much larger Mount Pinatubo-derived aerosol cloud(~28Mt) [*McCormick et al.*, 1995; *Zhao et al.*, 1995]. Thus if amplification of ENSO phenomena by volcanic aerosols is possible, it is not a direct cause and effect relationship. ENSO phenomena arise through ocean-atmospheric system interactions in the tropical Pacific [e.g. *Neelin et al.*, 1994] under conditions without volcanic perturbations of the atmosphere.

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References

Angell, J. K., Variation in global tropospheric temperature after adjustment for the El Niño influence, 1958-89, *Geophys. Res. Lett., 17,* 1093-1096, 1990.

Graf, H-F., I. Kirchner, A. Robock, and I. Schult, Pinatubo eruption winter climate effects: Model versus observations, *Climate Dynamics, 9,* 81-93, 1993.

Graf, H-F., I. Kirchner, R. Sausen, and S. Schubert, The impact of upper-tropospheric aerosol on global atmospheric circulation, *Ann. Geophys, 10,* 698-707, 1992.

Handler, P., Possible association of stratospheric aerosol and El Niño type events, *Geophys. Res. Lett., 11*, 1121-1124, 1984.

Handler, P., Possible association between the climatic effects of stratospheric aerosols and sea surface temperatures in the eastern tropical Pacific ocean, *J. Climatol., 6,* 31-41, 1986.

Handler, P. The effect of volcanic aerosols on global climate, *J. Volc. Geotherm. Res., 37,* 233-249, 1989.

Handler, P., and K. Andsager, Volcanic aerosols, El Niño, and the Southern Oscillation, *International J. Climatol., 10,* 413-424, 1990.

Handler, P., and K. Andsager, Impact of volcanic aerosols on global climate, *Trends in Geophys. Res., 2,* 581-593, 1993.

Hirono, M., On the trigger of El Niño Southern Oscillation by the forcing of early El Chichón volcanic aerosols, *J. Geophys. Res., 93,* 5365-5384, 1988.

Kent, G. S., and M. P. McCormick, Remote sensing of stratospheric aerosol following the eruption of El Chichón, *Opt. News*, 11-19, May 1988.

Lyons, W. B., P.A. Mayewski, M. J. Spencer, M. S. Twickler, and T. E. Graedel, A northern hemisphere volcanic chemistry (1869-1984) and climatic implications using a South Greenland ice core, *Ann. Glac. 14,* 176-182, 1990.

McClelland, L., T. Simkin, M. Summers, E. Nielsen, and T. C. Stein, *Global Volcanism, 1975-1985*, 655 pp., Prentice Hall, Englewood Cliffs, New Jersey,1989.

McCormick, M. P., L. W. Thomason, and C. R. Trepte, Atmospheric effects of the Mt Pinatubo eruption, *Nature, 373*, 399-404, 1995.

Neelin, J. D., M. Latif, and F.-F. Jin, Dynamics of coupled ocean-atmosphere models: The tropical problem, *Ann. Rev. Fluid Mech., 26,* 617-659, 1994

Newhall, C. G., and S. Self, The Volcanic Explosivity Index (VEI): An estimate of explosive magnitude for historical volcanism, *J. Geophys. Res., 87,* 1231-1238, 1982.

Newhall, C. G., and D. Dzurisin, Historical unrest at large calderas of the world; Vols. 1 and 2, *U.S. Geol. Surv. Bull 1855,* 1108 pp., 1988.

Nicholls, N., Low latitude volcanic eruptions and the El Niño-Southern Oscillation, *J. Climatol., 8,* 91-95, 1988.

NOAA, El Niño and climate prediction, National Oceanic and Atmospheric Administration, Reports to the Nation, 3, 25 pp., 1994.

Quinn W. H., and V. T. Neal, The historical record of El Niño events, in *Climate Since A.D. 1500*, edited by R. S. Bradley and P. D. Jones, pp. 623-648, Routledge, London, 1992.

Quinn, W. H., D. O. Zopf, K. S. Short, and K. Yang, Historical trends and statistics in the Southern Oscillation, El Niño, and Indonesian droughts, *Fish. Bull., 76,* 663-678, 1978.

Rampino, M. R., and S. Self, Tambora 1815, Krakatau 1883 and Agung 1963: A study of volcanic eruptions, their stratospheric aerosols and climatic impact, *Quater. Res. 18,* 127-143, 1982.

Rasmusson E. M., and T. H. Carpenter, Variations in tropical sea surface temperature and surface winds associated with the Southern Oscillation/El Niño, *Mon. Wea, Rev., 110,* 354-384, 1982.

Rasmussen E. M., and J. M. Wallace, Meteorological aspects of El Niño/Southern Oscillation, *Science, 222,* 1195-1202, 1983.

Robock, A., and M. P. Free, Ice cores as an index of global volcanism from 1850 to the present, *J. Geophys. Res., 100,* 11,549-11,567, 1995.

Robock, A., and Y. Liu, The volcanic signal in Goddard Institute for Space Studies three-dimensional model simulations, *J. Climatol., 7,* 44-55, 1994.

Robock, A., and M. Matson, Circumglobal transport of the El Chichón volcanic dust cloud, *Science, 221,* 195-197, 1983.

Robock, A., K. E. Taylor, G. L. Stenchikov, and Y. Liu, GCM evaluation of a mechanism for El Niño triggering by the El Chichón ash cloud, *Geophys. Res. Lett., 22,* 2369-2372, 1995.

Sato, M., J. E. Hansen, M. P. McCormick, and J. B. Pollack, Stratospheric aerosol optical depths, 1875-1990, *J. Geophys. Res., 98,* 22,987-22,994, 1993.

Self, S., and A. J. King, Petrology and sulfur and chlorine emissions of the 1963 eruption of Gunung Agung, Bali, Indonesia, *Bull. Volc., 58,* 263-285, 1996.

Self, S., and M. R. Rampino, The relationship between volcanic eruptions and climate change: Still a conundrum? *Eos Trans. AGU, 69,* 74-75 and 85-86, 1988.

Sigurdsson, H., Evidence of volcanic loading of the atmosphere and climate response, *Palaeo., 89,* 277-289, 1990.

Simkin, T., L. Siebert, L. McClelland, D. Bridge, C. Newhall, and L. H. Latter, *Volcanoes of the World*, 232 pp., Hutchinson Ross, Stroudsburg, Penn., 1981.

Simkin, T., and L. Siebert, *Volcanoes of the World, Second edition,* 349 pp., Geoscience Press, Tuscon, Arizona, 1994.

Stoiber, R. E., and W. I. Rose, Cl, F, and SO_2 in Central American volcanic gases, *Bull. Volcanol., 37,* 454-460, 1973.

Stothers, R. B., Major optical depth perturbations to the stratosphere from volcanic eruptions: The pyrheliometric period, 1881-1960, *J. Geophys. Res., 101,* 3901-3920, 1996.

Wang, B., Interdecadal changes in El Niño onset in the last four decades, *J. Climate, 8,* 267-285, 1995.

Woodruff, S. D., R. J. Slutz, R. L. Jenne, and P. M. Sturer, A comprehensive ocean-atmosphere data set, Bull. Amer. Meteor. Soc., 68, 1239-1250, 1987.

Zhao, J., R. P. Turco, O. B. Toon, A model simulation of Pinatubo volcanic aerosol in the stratosphere, *J. Geophys. Res., 100,* 7315-7328, 1995.

Zielinski, G. A., Stratospheric loading and optical depth estimates of explosive volcanism over the last 2100 years derived from the GISP2 Greenland ice core, *J. Geophys. Res., 100,* 20,937-20,955, 1995.

Zielinski G. A., P. A. Mayewski, L. D. Meeker, S. Whitlow, M. Twickler, M. Morrison, D. Meese, R. B. Alley, and A. J. Gow, Record of volcanism since 7000 B.C. from the GISP2 Greenland ice core and implications for the volcano-climate system, *Science, 264,* 948-952, 1994.

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